TACCIMO Literature Report

Literature Report – Annotated Bibliography Format
Report Date: April 1, 2013

Content Selections:
FACTORS – Vegetation Management, Soil & Geologic Resources
CATEGORIES – Carbon Sequestration (MANAGEMENT OPTIONS)
REGIONS – National, East, R9: Eastern, North Atlantic, R8: Southern, South Atlantic, South Central

How to cite the information contained within this report

Each source found within the TACICMO literature report should be cited individually. APA 6th edition formatted citations are given for each source. The use of TACCIMO may be recognized using the following acknowledgement:

"*We acknowledge the Template for Assessing Climate Change Impacts and Management Options (TACCIMO) for its role in making available their database of climate change science. Support of this database is provided by the Eastern Forest Environmental Threat Assessment Center, USDA Forest Service.*"

Best available scientific information justification

Content in this Literature report is based on peer reviewed literature available and reviewed as of the date of this report. The inclusion of information in TACCIMO is performed following documented methods and criteria designed to ensure scientific credibility. This information reflects a comprehensive literature review process concentrating on focal resources within the geographic areas of interest.

Suggested next steps

TACCIMO provides information to support the initial phase of a more comprehensive and rigorous evaluation of climate change within a broader science assessment and decision support framework. Possible next steps include:

1. Highlighting key sources and excerpts
2. Reviewing primary sources where needed
3. Consulting with local experts
4. Summarizing excerpts within a broader context

More information can be found in the user guide. The section entitled Content Guidance provides a detailed explanation of the purpose, strengths, limitations, and intended applications of the provided information.

Where this document goes

The TACCIMO literature report may be appropriate as an appendix to the main document or may simply be included in the administrative record.

Brief content methods

Content in the Literature Reports is the product of a rigorous literature review process focused on cataloguing sources describing the effects of climate change on natural resources and adaptive management options to use in the face of climate change. Excerpts are selected from the body of the source papers to capture key points, focusing on the results and discussions sections and those results that are most pertinent to land managers and natural resource planners. Both primary effects (e.g., increasing temperatures and changing precipitation patterns) and secondary effects (e.g., impacts of high temperatures on biological communities) are considered. Guidelines and other background information are documented in the user guide. The section entitled Content Production System fully explains methods and criteria for the inclusion of content in TACCIMO.

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Monday, April 01, 2013

RESOURCE AREA (FACTOR): SOIL & GEOLOGIC RESOURCES

CARBON SEQUESTRATION

NATIONAL

Hyvonen, R., Agren, G. I., Linder, S., Persson, T., Cotrufo, M. F., Ekblad, A., . . . Wallin, G. (2007). The likely impact of elevated [co2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: A literature review. New Phytologist, 173, 462-480.

Intensively managed forests behave as strong C sources following clear-cutting and site-preparation operations. They reach their maximal C-sink strength earlier than lightly managed or unmanaged forests.

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

Forest management practices designed to achieve mitigation goals of reducing greenhouse gases (CO_2 in particular) are diverse, and have large potential mitigation contributions on the global to regional scales (Malhi, Meir, and Brown, 2002; Krankina and Harmon, 2006).

The only legislatively required analysis with respect to climate change and USFS (United States Forest Service) planning was identified in the 1990 Food Protection Act, which amended the 1974 Resources Planning Act (RPA). The 1990 Act required the USFS to assess the impact of climate change on renewable resources in forests and rangelands, and to identify the rural and urban forestry opportunities to mitigate the buildup of atmospheric CO_2.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. Science, 1623-1627.

Common RMPs [resource management plans] that lead to SOC [soil organic carbon] sequestration are mulch farming, conservation tillage, agroforestry and diverse cropping systems, cover crops (Fig. 3), and integrated nutrient management, including the use of manure, compost, biosolids, improved grazing, and forest management.

Neilson, E. T., MabLean, D. A., Meng, F., Hennigar, C. R., & Arp, P. A. (2008). Optimal on- and off site forest carbon sequestration under existing timber supply constraints in Northern New Brunswick. Can. J. For. Res., 38, 2784-2796.

Forests could be managed to increase on-site C sequestration through silviculture interventions.

Newell, R. G., & Stavins, R. N. (2000). Climate change and forest sinks: Factors affecting the costs of carbon sequestration. Journal of Environmental Economics and Management, 40(3), 211-235.

Importantly, retarded deforestation can sequester carbon at substantially lower costs than increased forestation.

Sohngen, B., & Mendelsohn, R. (2003). An optimal control model of forest carbon sequestration. American Agricultural Economics Association, 85, 448-457.

This study finds that the two most important factors in carbon sequestration are land-use change and lengthening rotations.

RESOURCE AREA (FACTOR): VEGETATION MANAGEMENT

CARBON SEQUESTRATION

NATIONAL

Birdsey, R., Pregitzer, K., & Lucier, A. (2006). Forest Carbon Management in the United States: 1600–2100. Journal of Environmental Quality, 35(4), 1461-1469. doi:10.2134/jeq2005.0162

This means there may be opportunities to manage respiration following disturbance, for example, by minimizing respiration of soil C through management practices, utilizing harvest residue (slash) in ways that decrease the flux of C back to the atmosphere, or accelerating net primary productivity through intensive management practices or genetics to offset the pulse of microbial respiration following harvest.

The forest sector includes a variety of activities that can contribute to increasing carbon sequestration, including: afforestation, mine land reclamation, forest restoration, agroforestry, forest management, biomass energy, forest preservation, wood products management, and urban forestry (Birdsey et al., 2000). Taken together, this group of forestry activities could potentially increase carbon sequestration by 100 to 200 Tg C/yr, more than enough to offset projected declines in the sequestration rate by the forest sector of the United States.

D'Amato, A. W., Bradford, J. B., Fraver, S. & Palik, B. J. (2011). Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. Forest Ecology and Management, 262, 803-816.

Collectively, these findings underscore the importance of avoiding rigid adherence to a single objective, such as maximum on-site carbon stores, without recognizing potential consequences to other ecosystem components crucial to ensuring long-term ecosystem functioning within the context of environmental change. One potential stand-level strategy for balancing these goals may be to employ multi-aged management systems, such as irregular shelterwood and selection systems, that maintain a large proportion of carbon stores in retained mature trees while using thinning to create spatial heterogeneity that promotes higher sequestration rates in smaller, younger trees and simultaneously enhances structural and compositional complexity.

Depro, B. M., Murray, B. C., Alig, R. J., & Shanks, A. (2008). Public land, timber harvests, and climate mitigation: Quantifying carbon sequestration potential on U.S. public timberlands. Forest Ecology and Management, 255, 1122-1134.

Our analysis found that a "no timber harvest" scenario eliminating harvest on public lands would result in an annual increase of 17-29 million metric tonnes of carbon (MMTC) per year between 2010 and 2050 - as much as 43% increase over current sequestration levels on public timberlands and would offset up to 1.5% of total U.S. GHG emissions.

Evans, A. M. & Perschel, R. (2009). A review of forestry mitigation and adaptation strategies in the Northeast U.S. Climatic Change, 96(1), 167-183. doi:10.1007/s10584-009-9569-3

The fate of wood products removed from the forest and the carbon emitted in the transportation and manufacture of wood products has a major impact on the carbon accounting for forest management. Solid wood and wood composite products store carbon for 45–100 years while wooden pallets have a half life of 6 years (Skog and Nicholson 1998; Houghton and Hackler 2000; Penman et al. 2003) and paper decays at a rate of about 10% per year (Houghton and Hackler 2000).

Galik, C. S. & Jackson, R. B. (2009). Risks to forest carbon offset projects in a changing climate. Forest Ecology and Management, 257(11), 2209-2216. doi:10.1016/j.foreco.2009.03.017

In even-aged management systems, longer rotations generally lead to greater amounts of carbon sequestration in aboveground biomass. The optimal rotation length for a particular stand, however, depends on discount rate, timber price, carbon price, and treatment of wood products under an offset program.

In an even-aged stand, thinning to a specified relative density from below can result in greater sequestration than thinning from above, even when accounting for wood products, dead wood, and debris (Hoover and Stout, 2007).

Fertilization can also play a role in the management of forests for carbon sequestration, especially under changing atmospheric conditions. Research shows that fertilization may improve tree biomass accumulation under elevated CO_2 levels (Oren et al., 2001; Maroco et al., 2002). Under some trading programs, however, the emissions tied to the use of synthetic fertilizer are also factored into some projects, potentially lowering the net GHG [greenhouse gas] benefit of an offsets project (Voluntary Carbon Standard, 2007).

In addition to the management techniques outlined above, the choice of species will influence the rate and amount of carbon sequestered on a site. Liski et al. (2004) find that the maximum combined carbon sequestration of Scots pine [Pinus sylvestris] and Norway spruce [Picea abies] soil, vegetation, and forest product pools are generated under different rotation lengths; of 60, 90, or 120 year rotations, Scots pine is found to sequester the greatest amounts in 120 year rotations and Norway spruce in 60 year rotations.

Finally, the use of mixed species or mixed age stands has the potential to increase rates of sequestration. Kelty (2006) documents that stand productivity can be increased through the use of species mixes that either more fully utilize limited site resources (complementary) or that physically benefit the growth of another (facilitative). For instance, management for stratified, multistoried canopies may achieve greater sequestration through maximization of leaf area (Helms, 1996; Malmsheimer et al., 2008).

Hyvonen, R., Agren, G. I., Linder, S., Persson, T., Cotrufo, M. F., Ekblad, A., . . . Wallin, G. (2007). The likely impact of elevated [co2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: A literature review. New Phytologist, 173, 462-480.

Any measures increasing the productivity of the forest ecosystem may increase C sequestration in the forest (Johnson et al., 2002; Paul et al., 2003). Therefore higher stocking throughout the rotation is preferable if management aims at a high C-sequestration capacity in the forest ecosystem. The productivity of forest ecosystems may be increased through fertilization which, in the form of N combined with other nutrient elements, may drastically increase forest growth in the boreal and temperate regions (Tamm, 1991; Linder, 1995; Bergh et al., 1999; Jarvis & Linder, 2000).

The choice of tree species that are planted and the resulting stand composition may have a major impact on the C-sequestration capacity of the forest ecosystem. For example, mixing birch [Betula spp.] or other deciduous species with spruce [Abies spp.] and pine [Pinus spp.] may enhance C sequestration (de Wit & Kvindesland 1999). On the other hand, forest ecosystems dominated by conifers may, in many cases, sequester C even more effectively and store C longer than ecosystems dominated by deciduous trees. This is because the growth rate of many coniferous species is higher over longer periods than that of many deciduous species (cf. Cannell, 1989).

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

Projects planned to delay return of CO2 to the atmosphere (e.g., by lengthening rotation) both in situ (in forest or plantation) and post-harvest, are most successful.

McKinley, D. C., Ryan M. G., Burdsey,R. A., Giardina, C. P., Harmon, M. E., Heath, L. S., Houghton, R. A., Jackson, R. B., Morrison, J. F., Murray, B. C., Pataki, D. E., & Skog, K. E. (2011). A synthesis of current knowledge on forests and carbon storage in the United States. Ecological Applications, 21(6), 1902-1924.

Avoided deforestation protects existing forest carbon stocks with low risk and many co-benefits. Important risks are the potential for leakage (deforestation can move elsewhere with no lowering of atmosphere [CO2]) and lost economic opportunities for timber, agriculture, pasture, or urban development (Meyfroidt et al. 2010). Leakage estimates (percentage of carbon benefit lost) for avoided deforestation, without allowing harvest, range from 9% to 92% for different U.S. regions (Murray et al. 2004). In the United States, regenerating forests after severe wildfires may be important for avoiding conversion of forest to meadow or shrubland (Keyser et al. 2008, Donato et al. 2009).

Afforestation stores carbon and has some benefits (including erosion control and improving water quality), few risks and uncertainties, but some trade-offs. Afforestation on historical forestland generally has the greatest co-benefits, lowest risk, and fewest trade-offs. The benefits of afforestation are enhanced where seedlings established, whether by planting or natural regeneration, include a substantial proportion of native species appropriate to the site.

Decreasing removal of carbon from forests through longer harvest intervals or less intense harvests will increase forest carbon stocks. Benefits of the decreased outputs strategy include an increase in structural and species diversity. Increased risks include carbon loss due to disturbance and the potential for increased harvesting elsewhere (leakage) to compensate for the reduction in forest products.

The benefits of increasing forest growth include the opportunity to increase wood production, possibly greater carbon stocks, and opportunity to plant species and genotypes adapted to future climates. Risks include reducing the carbon benefit by emissions of nitrous oxide from forest fertilization, reduced water yield (faster growth uses more water), which is more pronounced in arid and semiarid forests in the western United States, and a loss of biodiversity if faster growth is accomplished by replacing multispecies forests with monocultures (limited diversity can make some forests vulnerable to rapid environmental change and to insect and disease epidemics).

Millar, C. I., Stephenson, N. L., & Stephens, S. L. (2007). Climate change and forests of the future: Managing in the face of uncertainty. Ecological Applications, 17(8), 2145-

One obvious means of slowing this release of sequestered carbon is to increase forest resistance to fire, drought, and disease, usually by reducing the density of small trees. In roaded or otherwise accessible areas, such density reductions might be accomplished by mechanical thinning, prescribed fires, or both (Stephens and Moghaddas 2005b). In remote or rugged terrain, wildland fire use or appropriate management response suppression fire may be the only reasonable option (Collins et al. 2007). In either case, some carbon inevitably will be released in the process of increasing forest resistance to sudden release of much greater quantities of carbon. If small trees are physically removed during the density reduction, then subsequently used for energy generation or long-term sequestration,the net carbon release might be minimized.

Moore, P. T., DeRose, R. J., Long, J. N., & van Miegroet, H. (2012). Using silviculture to influence carbon sequestration in southern Appalachian spruce-fir forests. Forests, 3(2), 300-316. doi:10.3390/f3020300

While managed forests are not expected to contain as much standing carbon (C) as old-growth forests on similar sites, managed forests could potentially sequester more C when both live biomass and harvested biomass are considered, and depending on the fate of harvested biomass (e.g., biofuel versus structural wood products, [Van Deusen 2010, Sorenson et al. 2011]). Furthermore, if the rate of growth for live biomass is increased by active management for wood products, the potential C sequestration rates in managed forests might be increased.

By maintaining stand stocking within a desired range of relative stand density associated with various levels of growth potential (i.e., maximum tree growth versus maximum stand growth, [Long 1985]) silviculturists can potentially influence the rate of C [carbon] sequestration.

For example, if just considering TC (total C [carbon]), i.e., C pool size, dense, older stands would likely be considered the largest C pools. On the other hand, if the focus was on AAC (average annual changes in C), i.e., the rate of C accumulation, young, rapidly growing stands are likely to accumulate C faster, even if their TC is lower [Kolari et al. 2004].

Neilson, E. T., MabLean, D. A., Meng, F., Hennigar, C. R., & Arp, P. A. (2008). Optimal on- and off site forest carbon sequestration under existing timber supply constraints in Northern New Brunswick. Can. J. For. Res., 38, 2784-2796.

A scenario that maximized on-site forest C sequestration for 80 years, respecting "business-as-usual" harvest constraints, projected an extra 3 t C(ha^-1) across the forest management area compared with the business-as-usual scenario, with net C storage potential (forest C + forest C in products - emissions produced from decayed wood products) resulting in approximately 1 Mt C. A scenario to double softwood harvest led to a projected decrease in the forest C pool by approximately 5 t C(ha^-1) from 2007 to 2082 and overall storage decrease of almost 2 Mt C from the base run. Other scenarios to increase or decrease harvest volumes by 10% resulted in overall C storage increases of 1.6 Mt C and almost 2.7 Mt C, respectively, above the base run. All scenarios resulted in net sinks of C after the 80 year simulation.

Silvicultural methods designed to accelerate timber growth are expected to increase the aboveground C sequestration capability of commercial forests.

Our results indicate that on-site C stocks could be increased by 3 t C (ha^-1) on the land base without compromising other socioeconomic constraints and objectives.

Newell, R. G., & Stavins, R. N. (2000). Climate change and forest sinks: Factors affecting the costs of carbon sequestration. Journal of Environmental Economics and Management, 40(3), 211-235.

We find, somewhat counter intuitively, that the costs of carbon sequestration can be greater if trees are periodically harvested, rather than permanently established.

Pohjola, J., & Valsta, L. (2006). Carbon credits and management of scots pine and norway spruce stands in finland. Forest Policy and Economics, 9(7), 789-798.

Although approximate, our analysis strongly indicated that delaying and lightening thinnings had a major contribution to increasing carbon sequestration and obtaining discounted incomes from carbon sequestration in the case of Scots pine [Pinus sylvestris].

Post, W. M., Izaurralde, R. C., West, T. O., Liebig, M. A. & King, A. W. (2012). Management opportunities for enhancing terrestrial carbon dioxide sinks. Frontiers in Ecology and the Environment, 10 (10), 554 – 561. doi:10.1890/120065

Forestry activities that promote C [carbon] storage include afforestation, reforestation, deforestation avoidance, replacing fossil fuels with biomass energy, wood products management, and improved forest management. This group of forestry activities could potentially increase C sequestration in the US by 370–740 Tg CO2eq yr–1 (Birdsey et al. 2007). Protecting forests from wildfire increases C stocks in the short term but, combined with climate-change effects, may also increase the risk of large future releases of stored CO2 during fire events (Westerling et al. 2006), bark beetle or other defoliating insect outbreaks, hurricanes, ice storms, droughts, and other disturbances. Afforestation, particularly on abandoned agricultural land, reclaimed mine sites, and other degraded lands, generally increases soil C in addition to producing wood (Guo and Gifford 2002). Avoiding deforestation and forest degradation preserves existing C stocks that would otherwise be lost to the atmosphere

A full accounting of the effects of different management actions on C storage requires knowledge of ecosystem C pools (Johnson and Curtis 2001; Echeverria et al. 2004); harvested wood products (Schlamadinger and Marland 1996); fossil-fuel GHG emissions associated with growing, harvesting, and manufacturing (Schlamadinger et al. 1997); and their potential future changes.

Specific forest management techniques to improve C sequestration – thereby enhancing productivity, improving disease control, reducing decomposition and respiration, and managing wildfires – include the following: managing nutrients and water, performing residue management (eg the use of wood to offset fossil fuels), thinning and utilizing the products from thinning, low impact harvesting, optimizing rotation length, administering species selection, and modifying genotype through biotechnology (Stanturf et al. 2003).

Van Kooten, G. C., Binkley, C. S., & Delcourt, G. (1995). Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. Ameri J Agr Econ, 77, 365-374.

In general, inclusion of the external benefits from carbon uptake results in rotation ages only a bit longer than the financial (Faustmann) rotation age.

NORTH CENTRAL

Williams, R. A., & Tao, Y. (2011). A Carbon Management Diagram for Oak-hickory Forests in Southern Ohio. Northern Journal of Applied Forestry, 28(3), 161-165.

The total carbon stock is positively correlated to basal area and average stand diameter but poorly correlated to the number of trees per acre. The total amount of carbon stored in these [Southern Ohio] forests is going to be influenced by age and site quality to the extent that age and site influence basal area and the average tree size. Accordingly, not all stands considered to be fully to overstocked store the most carbon. Rather, it is a combination of basal area and average tree size that determines the total carbon stored, with the carbon stock in the forest increasing with an increase in both basal area and average tree diameter.

R8: SOUTHERN

Aspinwall, M. J., McKeand, S. E., & King, J. S. (2012). Carbon sequestration from 40 years of planting genetically improved loblolly pine across the southeast United States. Forest Science, In Press. doi:10.5849/forsci.11-058

However, intensively managed, genetically improved plantations have high C [carbon] accumulation rates (Ryan et al. 2010), which may result in more efficient and cost-effective wood production and less harvesting on other forest lands. Thus, the higher productivity of genetically improved stands may provide an indirect C sequestration benefit to other forests by reducing harvesting pressures and maximizing C accumulation.

Keyser, T. L. & Zarnoch, S. J. (2012). Thinning, Age, and Site Quality Influence Live Tree Carbon Stocks in Upland Hardwood Forests of the Southern Appalachians. Forest Science, 58(5), 407-418. doi:10.5849/forsci.11-030

As a result of the thinning [of upland hardwood stands throughout southern Appalachian Mountains], ATC stocks [Carbon storage in the aboveground live tree pool] in thinned stands, which averaged 61 Mg/ha before thinning, were reduced by an average of 43% immediately after the thinning.

Although ATC stocks [aboveground total Carbon storage] increased in all stands [of upland hardwood throughout southern Appalachian Mountains over the 30-year study period], the rate at which thinned and unthinned stands accumulated ATC differed. Between 1975, immediately postthinning, and 2005, unthinned stands accumulated ATC at a net rate of 38 and 42% when ingrowth was excluded and included, respectively (Table 1). This rate is markedly slower than that for the thinned stands for which ATC stocks increased at an average net rate of 125% when ingrowth was excluded and 148% when ingrowth was considered over the 30-year period.

Average net annual ATC [aboveground total Carbon storage] increments observed in this study [of upland hardwood stands throughout southern Appalachian Mountains] are substantially greater than Carbon (C) uptake storage rates reported for northern hardwood forests in the eastern United States (Hoover and Stout 2007, Nunery and Keeton 2010), emphasizing the variability in landscape-level C uptake and storage potential known to occur among forest types and physiographic regions (Wofsy et al. 1993, Greco and Baldocchi 1996).

In general, relatively light levels of low thinning [of mixed-species upland hardwood stands throughout southern Appalachian Mountains] had a neutral to slightly positive effect on long-term postthinning ATC [aboveground total Carbon storage] stocks relative to their unthinned counterparts regardless of whether or not ingrowth data were included in the estimation of ATC stocks.

It appears from this study [of upland forest stands in southern Appalachian Mountains] that thinning coupled with an extended rotation age is a management action that may be used to increase live tree C stores (e.g., Harmon et al. 2009, Ryan et al. 2010).

Nepal, P., Grala, R. K., & Grebner, D. L. (2012). Financial feasibility of increasing carbon sequestration in harvested wood products in Mississippi. Forest Policy and Economics, 14(1), 99-106. doi:10.1016/j.forpol.2011.08.005

Primary wood product categories such as lumber, plywood and OSB [oriented-strand boards], stored larger amounts of carbon than paper, NSP [non-structural panels], and other products. Development of wood processing technology that increases the amount of these products would promote a greater accumulation of carbon in wood products. Strategies can, therefore, be aimed at improving technology used in forest operations and wood processing allowing for the reuse of by-products from thinning, harvesting and processing, and converting them into wood products with longer life cycles such as OSB.

NORTH ATLANTIC

Davis, S. C., Hessl, A. E., Scott, C. J., Adams, M. B., & Thomas, R. B. (2009). Forest carbon sequestration changes in response to timber harvest. Forest Ecology and Management, 258, 2101-2109. doi:10.1016/j.foreco.2009.08.009

Total C sequestered (or ∫ NEP [Net Ecosystem Productivity]) in the clear-cut watershed since 1958 was about 12% higher than the total C sequestered in the reference watershed (Fig. 4). Both the diameter-limit and selectively harvested watersheds had 37% higher total C stored than that estimated for the reference.

The long-term C balances of the four watersheds were similar except in the case of the clear-cut watershed (Table 4). Gross primary productivity (GPP) of the clear-cut watershed was about 35% lower than GPP of the other three watersheds (ANOVA: $F = 19.84$, $p < 0.0001$; Tukey HSD: $a = 0.05$, $Q = 2.5932$). Before the clear-cut event (before 1963), GPP in the clear-cut watershed was only about 17% lower than the long-term average in the other watersheds, so clear-cutting appears to correspond to a 22% decline in GPP (after 1969). The clear-cut harvest induced a decline in both NPP and respiration, but declines in respiration were much greater so that the average postharvest NEP of the clear-cut watershed was 138% greater than average NEP preharvest and 51% greater than the long-term average NEP of the reference watershed (Table 4).

The diameter-limit cut and selective cut watersheds both had stimulated productivity over the long-term, including increases in GPP, NPP, and NEP. However, short-term productivity responses to harvest (in the years between the first and second harvest) were negative so that NEP of the single tree selection and diameter-limit cut watersheds was 70% and 45% lower than the control watershed NEP, respectively (Table 4). Over time, the recovery periods following each harvest offset the short-term reduction in C sequestration.

Harvest events had a significant effect on short-term forest C storage rates, but the average annual rate of ecosystem C sequestration (NEP) over 55 years was similar in harvested and un-harvested forests (Fig.

Despite the eventual stimulation of NEP following the clear-cut, there was a net decline in the plant C component because all aboveground biomass was removed. Without recovery and maintenance of plant C, repeated clear-cutting, even 45 years later, would lead to a decline in the future growth potential. Intense harvests, like clear-cuts, have a greater effect on ecosystem C balances than less intense, but more frequent, harvests like diameter-limit cuts and single tree selection. There was no sustained decline in plant C following diameter-limit and single tree selection cuts (Fig. 5), suggesting that these lower intensity harvest techniques may be a more sustainable way to cut timber and minimally impact C sequestration in managed forests.

Troendle et al. (1974) found that soil losses immediately following the clear-cut in WS 7 were insignificant. Despite no effect on total soil C, temporary growth suppression with herbicides did affect the new organic matter additions to the soil immediately after harvest (Troendle et al., 1974), and thus the overall ecosystem C sequestration changes estimated in this study could be lower than those resulting after typical clear-cut events. In any case, the clear-cut harvest resulted in greater loss of organic matter (even after herbicide treatments ended) that would otherwise have been used as nutrients in future growing seasons. Thus, the plant C following the clear-cut treatment remained lower than the amount estimated in the other management treatments and may indicate a reduction of site quality.

If the wood removed from the watersheds was converted to long-standing wood products like furniture or structural materials, then the wood removed would be an additive contribution to carbon storage (C sink). On the other hand, wood that is burned or converted to short-lived products represents a negative contribution to the carbon budget (C source).

Carefully managed harvests affect short-term forest C budgets, but do not significantly impact average annual C sequestration rates over the long-term (~55 years). Total C sequestered over a 55-year period was stimulated ~37% by both diameter-limit cutting and selective cutting relative to the reference watershed. There was a stimulation of C storage following clear-cutting that offset C losses due to harvest, but repeated clear-cuts would not be sustainable because there was also a significant decline in plant C.

Evans, A. M. & Perschel, R. (2009). A review of forestry mitigation and adaptation strategies in the Northeast U.S. Climatic Change, 96(1), 167-183. doi:10.1007/s10584-009-9569-3

The North East State Foresters Association (2002) states that, in general, “management strategies that encourage larger trees, employ harvest methods that reduce waste and damage to residual trees, and minimize soil disturbance during harvest all improve carbon sequestration activities.”

Extending rotations or entry cycles and increasing the length of time trees grow before harvest can capture more carbon on site (Liski et al. 2001; Sampson 2004; Stavins and Richards 2005; Bravo et al. 2008). A potentially large amount of carbon could be sequestered in a relatively short time period by increasing the rotation ages of softwood stands beyond financially optimal ages. Studies looking at increasing rotation ages 5, 10, and 15 years indicate 3 Mg/ha/yr CO_2 can be sequestered by increasing the rotation age of softwoods in the Northeast (Sohngen et al. 2007). However, in some forests shorter rotations can increase the carbon held in soils because of litter production and harvest residues (Liski et al. 2001).

Any harvest reduces on site carbon storage, but depending on the fate of wood products harvested and the other materials or fuels the wood products replace, forest management can be a net carbon benefit (Harmon and Marks 2002; Schmid et al. 2006). A thin from below and a thin from the middle in Alleghany hardwoods increased the carbon stores 38 Mg/ha and 7.5 Mg/ha respectively when wood products were included (Hoover and Stout 2007).

Stoy, P. C., Katul, G. G., Siqueira, M. B. S., Juang, J. -Y., Novic, K. A., McCarthy, H. R., … & Oren, R. (2008). Role of vegetation in determining carbon sequestration along ecological succession in the southeastern United States. Global Change Biology, 14, 1-19. doi: 10.1111/j.1365-2486.2008.01587.x

Our analysis suggests that PP [planted pine]-type ecosystems may not significantly increase regional C sequestration if they replace HW-[hardwood forest] type forests, assuming similar future climatic variability. Actively managed PP-type ecosystems are smaller C pools than mature forests, and may also be smaller C sinks, especially when considering the strong atmospheric C source after clear-cutting (Lai et al., 2002a; Clark et al., 2004), the short rotation length of their management, and their sensitivity to drought and ice storm damage (Oren et al., 1998; McCarthy et al., 2006). The conservation of species-rich hardwood-type forests may be a sensible strategy for maintaining high C sequestration in the SE [Southeast]. These forests are already large pools of C, and C additions to these pools are less affected by climatic extremes, at least within the semi-decadal time scales considered here.

Vanderberg, M. R., Boston, K., Bailey, J. (2011). Maximizing carbon storage in the Appalachians: A method for considering the risk of disturbance events (General Technical Report NRS-P-78). In: Fei, S., Lhotka, J.M., Stringer, J.W., Gottschalk, K.W., Miller, G.W., eds. Proceedings, 17th central hardwood forest conference, 2010 April 5-7, Lexington, KY. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 134-142.

A no-management scenario in disturbance-prone forests of the Appalachian forest region includes the risk of fire, windthrow, ice damage, and pest outbreaks, as well as the carbon emissions associated with such disturbances.

The analysis and optimization procedure yielded silvicultural regimes to maximize carbon storage for each Southern Appalachian PNVG [Potential Natural Vegetation Groups]. Incorporating only the risk of fire, we determined that 9 of the 11 forest types showed the maximum carbon storage under the no-treatment scenario (Fig. 2). The two forest types that showed maximum carbon under treatment scenarios were R8OKAW (oak-ash-woodland [Quercus-Fraxinus]) and R8PIVIap (Appalachian Virginia pine [Pinus virginiana]). Adding the risk of other disturbance to the risk of fire, we determined that an additional three forest types showed the maximum carbon storage under treatment scenarios. The three forest types were R8FPFOpi (bottomland hardwood forest), R8MMHW (mixed mesophytic hardwood), and R8SAHE (Southern Appalachian high-elevation forest).

The results of this analysis suggest that in some cases, treating the forest over time may be beneficial in reducing the risk of carbon emissions due to disturbance events.

Treating the oak[Quercus]-ash[Fraxinus]-woodland showed the potential for increasing carbon stocks by nearly 7 percent over the control, while treating the Appalachian Virginia pine [Pinus virginiana] increased stocks by just over 2 percent. Treatment regimes that incorporated the total disturbance risk maximized carbon storage for three more forest types while increasing the expected stocks by an additional 12 to 19 percent for the oak-ash-woodland and Appalachian Virginia pine stands. Of the three additional forest types, the bottomland hardwood forest increased carbon stocks by nearly 12 percent over the control. The Southern Appalachian high-elevation forest and mixed mesophytic hardwood forest types increased stocks by 1.5 to 3.0 percent over the control.

The best method for maximizing terrestrial-based forest carbon stocks depends on the type of forest being analyzed. Appalachian forests with a low mDRI [mean disturbance return interval] (i.e., less than 20 years) were shown to store more carbon by way of no treatment over the analysis period. A logical explanation could be that the mortality rates associated with frequent disturbances are lower than or close to the treatment intensities. Similarly, Appalachian forests with a higher mDRI (i.e., greater than 20 years) were shown to store more expected carbon by way of a treatment regime, with the exception of

R8HEWP (hemlock [Tsuga]-white pine[Pinus strobus]-hardwood). This result may be explained by the hemlock-white pine-hardwood forest type exhibiting the second highest mDRI, but also having the second lowest mortality rate of those forests with a mDRI greater than 20 years.

The greatest potential for increasing carbon storage by way of a silvicultural regime exists in bottomland hardwood forests, oak-ash-woodlands, and Appalachian Virginia pine [Pinus virginiana] stands. Oak[Quercus]-ash[Fraxinus]-woodlands have the most potential, showing an increase of more than 26 percent over the control. When the no-management regimes stored more carbon compared to treated stands, there was no difference greater than 11 percent.

SOUTH CENTRAL

Nepal, P., Grala, R. K., & Grebner, D. L. (2012). Financial feasibility of increasing carbon sequestration in harvested wood products in Mississippi. Forest Policy and Economics, 14(1), 99-106. doi:10.1016/j.forpol.2011.08.005

The analysis [of forest stands in Mississippi] indicated that carbon stock both in standing trees and wood products can potentially be increased if loblolly pine [Pinus taeda] stands are managed with longer rotations. However, it was financially feasible only at carbon prices of $50/tCO2e and higher. If the stand was managed only for timber, it would be harvested at age 35 years and accumulate 659.43 tCO2e in standing trees and 160.84 tCO2e in wood products in use and landfills 100 years after harvest. Carbon payments of $50/tCO2e and $110/tCO2 provided a sufficient incentive to increase rotation age by 5 to 10 years, respectively, and potentially increase carbon sequestered in standing trees by up to 55.15 tCO2e/ha and wood products by up to 28.60 tCO2e/ha, relative to traditional rotation age of 35 years applied to stands managed for timber. In the state of Mississippi that has about 2.8 million ha of loblolly pine forests (USDA, 2010) such rotation increases can potentially translate to additional carbon accumulation of 154 million tCO2e in standing trees and 80 million tCO2e in wood products.

EAST

Evans, A. M. & Perschel, R. (2009). A review of forestry mitigation and adaptation strategies in the Northeast U.S. Climatic Change, 96(1), 167-183. doi:10.1007/s10584-009-9569-3

Another option to increase carbon storage is to increase the structural complexity of forests. Structural complexity and carbon storage can be increased by preserving reserve trees, snags, and CWM [coarse woody materials] (Harmon and Marks 2002; Park et al. 2005; Keeton 2006; Choi et al. 2007). Leaving reserve trees or groups adds to the current structural complexity of a stand and provides a source of CWM into the future (Keeton 2006; Salonius 2007). Uneven aged management is often used to promote structurally complex forests and may sequester more carbon. For example, uneven aged management stores 40 Mg/ha more carbon than clearcut even-age management in the oak-hickory [Quercus-Carya] and oak-pine [Quercus-Pinus] communities of the Ozarks (Li et al. 2007) and up to 26 Mg/ha more than diameter limit cutting in Wisconsin (Strong 1997).